ACTA GEOGRAPHICA SLOVENICA

GEOGRAFSKI ZBORNIK

2025

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ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK
65-3 • 2025

Contents

SPECIAL ISSUE – *The importance of common lands' management for sustaining ecosystem services*

POSEBNA IZDAJA – *Pomen upravljanja skupnih zemljišč za zagotavljanje ekosistemskih storitev*

ISSN 1581-6613
9 771581 661010

ACTA GEOGRAPHICA SLOVENICA

65-3
2025

ISSN: 1581-6613
UDC: 91
2025, ZRC SAZU, Geografski inštitut Antona Melika

Issued by/izdajatelj: Geografski inštitut Antona Melika ZRC SAZU
Published by/založnik: Založba ZRC
Co-published by/sozaložnik: Slovenska akademija znanosti in umetnosti

Address/naslov: Geografski inštitut Antona Melika ZRC SAZU, Gosposka ulica 13, p. p. 306, SI – 1000 Ljubljana, Slovenija; ags@zrc-sazu.si

The articles are available on-line/prispevki so dostopni na medmrežju: http://ags.zrc-sazu.si (ISSN: 1581–8314)

Ordering/naročanje: Založba ZRC, Novi trg 2, p. p. 306, SI – 1001 Ljubljana, Slovenija; zalozba@zrc-sazu.si

Annual subscription/letna naročnina: 20 €
Single issue/cena posamezne številke: 12 €

Cartography/kartografija: Geografski inštitut Antona Melika ZRC SAZU
Translations/prevodi: DEKS, d. o. o., Živa Malovrh
DTP/prelom: SYNCOMP, d. o. o.
Printed by/tiskarna: Cicero Begunje d. o. o.
Print run/naklada: 250 copies/izvodov

The journal is subsidized by the Slovenian Research and Innovation Agency (B6-7614) and is issued in the framework of the Geography of Slovenia core research programme (P6-0101)/Revija izhaja s podporo Javne agencije za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije (B6-7614) in nastaja v okviru raziskovalnega programa Geografija Slovenije (P6-0101).

The journal is indexed also in/revija je vključena tudi v: Clarivate Web of Science (SCIE – Science Citation Index Expanded; JCR – Journal Citation Report/Science Edition), Scopus, ERIH PLUS, GEOBASE Journals, Current geographical publications, EBSCOhost, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google Scholar, CrossRef, and DOAJ.

Design by/Oblikovanje: Matjaž Vipotnik

Front cover photography: Vezeira, the traditional migration of livestock, from the village of Pincães (Montalegre, Portugal) to high-altitude pastures is a community event organized to revive pastoral traditions and involve younger generations (photograph: Joana Nogueira).
Fotografija na naslovnici: Vezeira, tradicionalna selitev živine iz vasi Pincães na Portugalskem na visokogorske pašnike, ki jo izvaja lokalna skupnost, je namenjena oživitvi pašnih tradicij in vključevanju mlajših generacij (fotografija: Joana Nogueira).

Acta geographica Slovenica, 65-3, 2025, 75–91

THE CONTRIBUTION OF COMMON LANDS TO CARBON SEQUESTRATION: A CASE STUDY FROM TRIGLAV NATIONAL PARK IN SLOVENIA

Mateja Šmid Hribar, Daniela Ribeiro, Miguel Villoslada

MATEJA ŠMID HRIBAR

The Triglav National Park is dominated by forests and high mountains. In the foreground are the mountain pastures of Uskovnica, which are managed by the Agrarian Community Srednja Vas.

DOI: https://doi.org/10.3986/AGS.14491
UDC: 332.24.012.34:502.131.1(497.4)
630*111:546.26(497.4)

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The contribution of common lands to carbon sequestration: A case study from Triglav National Park in Slovenia

ABSTRACT: In this article, we explore the role of the Slovenian common lands managed by agrarian communities in providing ecosystem services. The study focuses on the Triglav National Park area with a fairly high proportion of common lands. We assessed the ecosystem service carbon sequestration, using MODIS Net Primary Production as a proxy, downscaled to a spatial resolution of 10 m. Despite the moderate overall carbon sequestration capacity of common lands, their forests and scrublands, which cover 14% of Triglav National Park and are characterised by higher productivity, play an important role due to their spatial extent. However, as Slovenia's forests have experienced a decline in carbon sequestration capacity since 2014, improved management by private owners, including agrarian communities, supported by national and EU funds, is key to strengthening this vital ecosystem service.

KEYWORDS: commons, governance, ecosystem services, carbon sequestration, forest, MODIS Net Primary Production, Slovenia

Prispevek skupnih zemljišč k zajemu in vezavi ogljika: študija iz Triglavskega narodnega parka v Sloveniji

POVZETEK: V tem članku preučujemo vlogo slovenskih skupnih zemljišč, s katerimi upravljajo agrarne skupnosti, pri zagotavljanju ekosistemskih storitev. Študija se osredotoča na območje Triglavskega narodnega parka z dokaj visokim deležem skupnih zemljišč. Ocenili smo ekosistemsko storitev zajem in vezava ogljika, pri čemer smo kot približek uporabili MODIS neto primarno produkcijo, zmanjšano na prostorsko ločljivost 10 m. Kljub zmerni skupni zmogljivosti zajema in vezave ogljika na celotnem območju skupnih zemljišč imajo njihovi gozdovi zaradi svojega velikega obsega – pokrivajo namreč 14 % Triglavskega narodnega parka – in višje neto primarne produkcije, pomembno vlogo. Vendar je zmogljivost slovenskih gozdov z vidika zajema in vezave ogljika po letu 2014 upadla, zato je za krepitev te pomembne ekosistemske storitve ključno izboljšati upravljanje zasebnih gozdov, vključno z gozdovi agrarnih skupnosti. Pri tem je nujna podpora nacionalnih in evropskih finančnih mehanizmov.

KLJUČNE BESEDE: srenja, upravljanje, ekosistemske storitve, zajem in vezava ogljika, gozd, MODIS neto primarna produkcija, Slovenija

The article was submitted for publication on June 4th, 2025.
Uredništvo je prejelo prispevek 4. junija 2025.

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1 Introduction

The European Union has set ambitious climate targets, aiming to reduce greenhouse gas emissions by 55% by 2030 and to achieve climate neutrality by 2050. Among the key strategies to meet these goals is the regulation of land use, land use change, and forestry (LULUCF; Regulation EU 2023/839). The LULUCF sector is particularly relevant, as it currently functions as a net carbon sink in the EU – absorbing more carbon than it emits. This is largely due to the capacity of vegetation, particularly forests, to absorb atmospheric carbon dioxide (CO_2) through photosynthesis. Forests provide a wide range of ecosystem services (Brockerhoff et al. 2017), of which carbon storage and sequestration has received particular attention in recent years due to its crucial role in mitigating climate change (Hu et al. 2022). Proper management of land resources is therefore essential to enhance the sector's contribution to climate mitigation. According to the current EU regulation on LULUCF from 2018, Member States are required to ensure that emissions from land use and forestry are balanced by an equivalent removal of CO_2. However, under the revised LULUCF Regulation, more ambitious targets have been set to enhance net greenhouse gas removals.

A detailed account of Slovenia's greenhouse gas emissions and removals, including key trends, is provided in Slovenia's National Inventory Document 2024 (2024). The LULUCF sector acts as a significant carbon sink, accounting for 95% of the LULUCF's total net removal. According to data from the Statistical Office forests, which covered approximately 58% of Slovenia's total area in 2023 thus play a crucial role in reducing greenhouse gas emissions. However, land use changes such as deforestation and natural disturbances, notably sleet, windstorms, and droughts since 2014, have reduced this potential. Pintar et al. (2025) showed that large-scale disturbances and subsequent sanitary felling can significantly affect regulating ecosystem services in Slovenian forests. As noted in the report, net removals from the LULUCF sector declined by 35% between 1986 and 2022 mainly due to decrease in sanitary felling and mortality rates (Slovenia's National Inventory ... 2024). While Slovenian climate policy participates in the EU Emissions Trading System, the LULUCF sector is currently not included in this mechanism. Instead, the LULUCF sector is governed by separate regulations and accounting rules within the EU (Regulation (EU) 2018/841). Rather than using market mechanisms, this requires countries to ensure that removals from forests and other land categories at least offset emissions. Additionally, according to United Nations, Slovenia supports, but has not yet implemented, the mechanisms of the Paris Agreement, which enables International Carbon Markets (Article 6.2) and Non-Market Approaches (Article 6.8). Regarding LULUCF commitments, Slovenia has set two national goals: 1) for the period 2021–2025, the objective is to ensure that emissions do not exceed removals; 2) for the period 2026–2030, Slovenia aims to achieve net removals, with a minimum of 0.14 million tonnes of CO_2 equivalent by 2030 (European Commission 2025).

According to the Slovenian Forest Service, 77% of Slovenian's forests are privately owned, 20% are state-owned, and 3% are owned by municipalities (Zavod za gozdove Slovenije 2024). The Slovenian state forest company (SiDG) is the most important forest owner in Slovenia, followed by the Ljubljana Archdiocese. However, agrarian communities are also notable forest owners. As in other Alpine regions and also other European countries, these communities predominantly manage the so-called 'forest commons', i. e. common forest lands (Bogataj and Krč 2014; Gatto and Bogataj 2015; Bogataj and Krč 2023; Nogueira et al. 2023; Pagot and Gatto 2024; Pagot et al. 2025; Šmid Hribar 2025). Bogataj and Krč (2014) demonstrated that, following the sleet storm in February 2014, agrarian communities in the Postojna regional forest district of the Slovenia Forest Service organised and harvested the damaged forests more quickly than other forest owners (with the exception of large-scale private owners).

In recent years, various primarily qualitative studies have recognised significant role of common lands in providing ecosystem services (Šmid Hribar et al. 2023; Pagot et al. 2025), as well as their importance for achieving the Sustainable Development Goals (Haller et al. 2021). Yet studies that approach this topic using quantitative assessments, such as in terms of ecosystem service provision, are lacking. One of such rare studies was presented by Pagot and Gatto (2024), who found that the attitudes of community-owned forest institutions towards providing forest recreation do not differ much from those of other private forest owners. Based on landscape analysis, Šmid Hribar (2025) revealed that common lands in Triglav National Park (TNP) make a significant contribution to biodiversity and nature conservation.

Therefore, the aim of this article is to contribute to a better understanding of the role of agrarian communities in providing ecosystem services, focusing particularly on carbon sequestration in protected areas, such as the TNP. The specific objectives of the study were 1) to assess ecosystem service carbon sequestration, which is classified under the Common International Classification of Ecosystem Services (CICES v5.2; code 2.3.6.1; Haines-Young 2023) in the TNP and 2) to determine the extent to which agrarian communities contribute to this ecosystem service.

2 Materials and methods

2.1 Study area

The research was conducted in the TNP, located in the northwestern Alpine region (Figure 1). Covering approximately 84,000 hectares, around 4% of Slovenia's territory, the TNP is divided into three protection zones, each with distinct management regimes (Table 1). The predominant land cover in the park is forest, followed by high (rocky) mountain areas (Table 3). This area was chosen primarily because common lands managed by agrarian communities make relatively high proportion – up to 24% of the park's total surface (Šmid Hribar 2025).

Despite its protection, the TNP supports various land uses, including economic, recreational, and tourism activities. Managing these uses requires careful negotiation and integration of multiple, and at times conflicting, interests. This multifunctionality underscores the need to assess and manage ecosystem services and thus ensure that conservation objectives are balanced with the sustainable use of natural and cultural resources. In this area, three ecosystem services – pollination, recreation, and fodder provision were assessed (Šmid Hribar et al. 2025). The main focus of this article is to assess carbon sequestration, which is currently perceived as one of the most essential ecosystem services for mitigating anthropogenic climate change due to greenhouse gas emmisions.

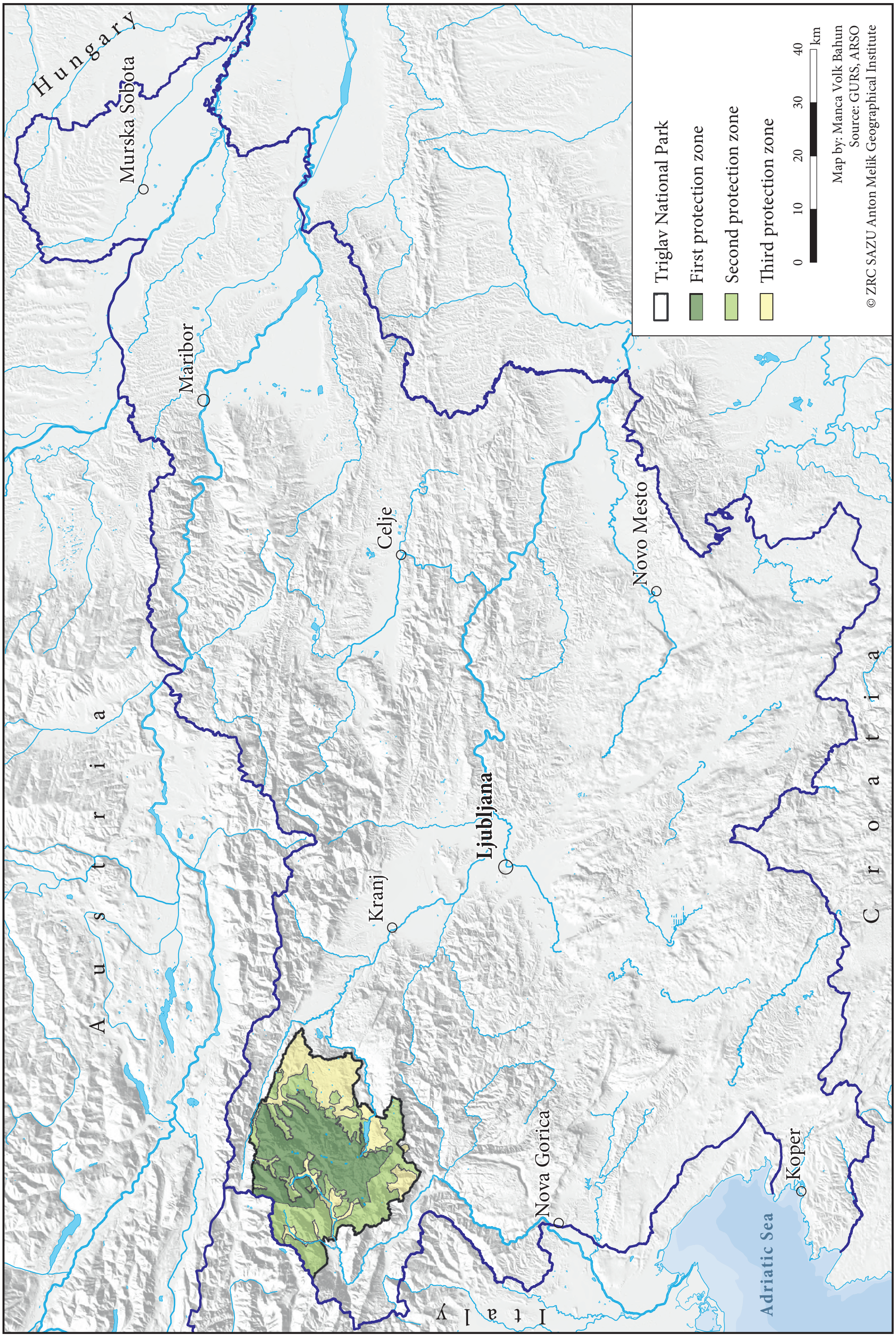
Table 1: Protection zones and their management in the TNP.

Protection zone	Management regime	Share in the TNP
First protection zone	Primarily intended for the protection and preservation of natural values, wilderness areas, species, habitats, and natural ecosystem processes without human intervention. Traditional grazing on managed mountain pastures and preservation of related cultural heritage are permitted.	37.5%
Second protection zone	It aims to preserve natural values and cultural heritage, prevent new burdens, and gradually align with the objectives of the first protection area. It also allows traditional resource use for environmentally friendly agriculture, forestry, and sustainable game and fish management.	38.6%
Third protection zone	It aims to preserve biodiversity, natural values and cultural heritage, landscape qualities, and settlements, while promoting sustainable development in line with national park objectives.	23.9%

2.2 Assessment of carbon sequestration in Triglav National Park

We assessed the carbon sequestration, which refers to the regulation of chemical composition of atmosphere and oceans, and the maintenance of continental atmospheric/oceanic circulation patterns, through the fixation and storage of carbon in plant biomass (Haines-Young 2023). Annual Net Primary Production (NPP) was used as a proxy for this service. NPP represents the net amount of carbon captured by plants through photosynthesis each year (Melillo et al. 1993; Cao and Woodward 1998), and thus expresses the carbon flux between the atmosphere and terrestrial vegetation (Goetz and Prince 1996). We acknowledge that NPP primarily captures the carbon uptake component of sequestration, and not the long-term storage in biomass and soils. It also does not explicitly consider losses of carbon due to heterotrophic respiration, decomposition or disturbances. Nevertheless, NPP provides a widely used and well-established proxy for

Figure 1: TNP, the only national park and the largest protected area in Slovenia, is located in the northwest of the country. ➤ p. 79


Triglav National Park
First protection zone
Second protection zone
Third protection zone
0 10 20 30 40 km
Map by: Manca Volk Bahun
Source: GURS, ARSO
© ZRC SAZU Anton Melik Geographical Institute
Hungary
Murska Sobota
Maribor
Celje
Novo Mesto
Ljubljana
Kranj
Nova Gorica
Koper
Austria
Croatia
Italy
Adriatic Sea

assessing ecosystems' contribution to climate regulation. We used MODIS NPP as a proxy for the carbon sequestration of each land use type, representing the ecosystem's annual contribution to global climate regulation. MODIS NPP data for the TNP were obtained through Google Earth Engine (GEE), using the MOD17A3HGF.061 product, which provides annual NPP allocated to both, above and below ground biomass at a spatial resolution of 500 m (De Leeuw et al. 2019). Annual NPP is derived from the sum of all 8-day net photosynthesis products for the year 2024 (Heinsch et al. 2003).

The coarse spatial resolution of the MODIS NPP product (500 m per pixel) limits its ability to capture the fine-scale mosaics of forest and agricultural land in the study area. To address this scale mismatch, we downscaled the MODIS NPP data to 10 m resolution, matching that of the EU Copernicus High Resolution Layers.

For the downscalling procedure, we selected a set of copredictors that are strongly linked to the vegetation productivity dynamics. To account for phenological events and dynamics, we utilized the High Resolution Vegetation Phenology and Productivity (HR-VPP) metrics provided by the Copernicus programme. The HR-VPP dataset consists of 13 raster layers at 10 m resolution, derived from Sentinel-2 image time series with a temporal resolution of five days. To produce the Plant Phenology Index (PPI) time series, the TIMESAT 4 algorithm is employed for smoothing and gap-filling (Jönsson and Eklundh 2004). Seasonal metrics are extracted by applying a sum of double logistic functions, which also delineate the phenological seasons (Jönsson et al. 2018). For a comprehensive description of the HR-VPP processing workflow, see Smets et al. (2023). From the HR-VPP collection, we selected six metrics (see Table 2 for more details), which we obtained from the WekEo data portal (https://www.wekeo.eu/).

In addition to the HR-VPP, we computed the median of three vegetation indices (Table 2) in GEE corresponding to the vegetation period June 1 – August 31, 2024, corresponding to the peak growing season. The indices were chosen for their good performance in previous studies, and their ability to distinguish relative differences in productivity, chlorophyll content, and vegetation density (Villoslada et al. 2024). The scenes used to compute the indices were obtained from the level 2A collection in GEE. We applied an atmospheric correction to obtain surface reflectance values using the Sen2Cor processor (Main-Knorn et al. 2017). We removed cloud and cloud shadow contamination by masking pixels based on cloud probability estimates from the Sentinel-2 dataset available in GEE, generated using the s2cloudless algorithm. Finally, we set the percentage of cloud cover threshold at 30%.

Once we compiled all the copredictors, we transformed the MODIS NPP scene into a vector grid, assigning each polygon the corresponding NPP value. We then calculated the median value of each copredictor within each vector cell to avoid pseudoreplication. To downscale the resolution of MODIS NPP and match

Table 2: Description of the copredictors used in this study to downscale MODIS NPP at 500 m per pixel to a spatial resolution of 10 m per pixel.

Co-predictor	Formula/Description	Reference
Season Amplitude	Corresponds to the difference between the maximum and the minimum Plant Phenology Index values reached during the growing season.	Smets et al. (2023)
Season Length	Corresponds to the number of days between the start and end of the season dates computed based on the Plant Phenology Index.	Smets et al. (2023)
Seasonal Productivity	Corresponds to the sum of daily Plant Phenology Index values during the growing season minus their base level value.	Smets et al. (2023)
Total Productivity	Corresponds to the sum of daily Plant Phenology Index values during the growing season.	Smets et al. (2023)
Maximum Season Value	The peak value reached by the Plant Phenology Index during the growing season.	Smets et al. (2023)
Start-of-Season date	Corresponds to the date when the Plant Phenology Index reaches 25% of the season amplitude during the green-up period.	Smets et al. (2023)
Normalised Difference Vegetation Index (NDVI)	(NIR – Red) / (NIR + Red)	Rouse et al. (1974)
Green Normalised Difference Vegetation Index (GNDVI)	(NIR – Green) / (NIR + Green)	Gitelson et al. (1996)
Enhanced Difference Vegetation Index (EVI2)	2.5 [(NIR – Red) / (NIR + 2.4 × Red + 1)]	Jiang et al. (2008)

it with that of the Copernicus High Resolution layers (10 m per pixel), we employed an Extreme Gradient Boost Algorithm (XGBoost). We selected the XGBoost algorithm for its effectiveness in regression tasks (Zhang et al. 2019) and its resilience to noise and class imbalance. Model development and spatial downscaling were carried out using the raster (Hijmans et al. 2015) and xgboost (Chen et al. 2019) packages in R. Hyperparameter tuning – covering learning rate, number of trees, minimum samples per leaf, maximum tree depth, number of features considered for splits, and gamma (γ) – was performed using the mlr package (Bischl et al. 2016) through 100 optimization rounds with five-fold cross-validation. To assess the importance of individual co-predictors in the XGBoost upscaling models, we used the Gain metric, which quantifies each variable's contribution to the predictive performance (Chen et al. 2019). Model training was conducted over 100 iteration rounds, using a randomly selected 20% subset of the original MODIS vector polygons to build the predictive model. This sampling strategy ensured sufficient generalization while minimizing spatial autocorrelation in the training data. All methodological steps were undertaken in R Studio 2024.09.1.

To validate the models, the XGBoost algorithm predicted a downscaled NPP map within each iteration round. Then, a different random set of MODIS NPP polygons (20% of the initial set, non-overlapping with the training set) was used to calculate the mean value of the downscaled NPP map within each MODIS polygon. In each iteration round we calculated R2, Root Mean Squared Error (RMSE), range-normalised RMSE (nRMSE), Mean Absolute Error (MAE), and bias. Finally, we calculated the mean of the validation metrics over all 100 iteration rounds. The final NPP downscaled map represents the mean of all maps produced through each model run.

Using the resulting 10 m resolution NPP data and land use data from the Ministry of Agriculture, Forestry and Food for 2024, we performed zonal statistics to calculate the average NPP for each land use type. To assess whether specific forest characteristics – such as protective forests that safeguard land from erosion, wind, flooding, and other hazards – influence carbon sequestration, we repeated the procedure using an additional dataset (Zavod za gozdove Slovenije 2024).

To facilitate the interpretation of spatial patterns, NPP values were classified using the Quantile method, which divides the dataset into intervals containing an equal number of observations. This approach ensures a uniform frequency distribution across classes, although class widths may vary depending on the underlying data distribution.

Water bodies and greenhouses were excluded from further analysis due to their marginal relevance to vegetation-based carbon dynamics and the inherent limitations of NPP models in aquatic environments.

2.3 Analysis of the role of agrarian communities in carbon sequestration in Triglav National Park

To assess the role of common lands in carbon sequestration, we analyzed mean NPP values on common land areas using Zonal Statistics in ArcGIS PRO. The shapefile of common lands in the TNP was obtained from Šmid Hribar (2025) and corrected from sliver polygons.

3 Results

3.1 Land use in Triglav National Park

The spatial analysis of land use revealed that forests dominate the TNP, covering 38,878.1 ha, which accounts for nearly half of the entire area (46.3%). They are followed by scrubland (15,908.9 ha; 18.9%), dried open areas with special vegetation (12,157.8 ha; 14.5%) and open areas with little or no vegetation (8,255.0 ha; 9.8%), mostly representing high-mountain terrain. These four land use categories together constitute 89.5% of the TNP. Among the remaining land uses, permanent grassland which include meadows and pastures (5,988.8 ha; 7.1%) stand out, as they give a significant character to the the TNP. Other land use categories are considerably smaller in extent (Table 3).

Table 3: Land uses in the TNP in 2024.

Land use	Area (ha)	Area (%)	% in protection zone 1	% in protection zone 2	% in protection zone 3
Arable land	12.51	0.0	0.0	5.0	95.0
Permanent crops on arable land	0.01	0.0	0.0	0.0	100.0
Greenhouse	0.05	0.0	0.0	0.0	100.0
Intensive orchard	1.37	0.0	0.0	5.1	94.9
Extensive orchard	50.84	0.1	0.0	1.1	98.9
Permanent grassland	5,988.84	7.1	18.8	41.7	39.6
Overgrown agricultural area	298.25	0.4	14.5	43.3	42.2
Trees and shrubs	293.23	0.3	6.1	27.8	66.1
Uncultivated agricultural land	65.83	0.1	1.6	24.2	74.1
Forest trees on agricultural land	1,004.76	1.2	41.7	44.7	13.7
Forest	38,878.10	46.3	18.5	41.7	39.8
Scrubland	15,908.88	18.9	57.7	37.2	5.0
Built-up area and related surface	479.65	0.6	2.1	14.3	83.6
Swamp	10.25	0.0	0.0	0.0	100.0
Other marshy area	0.38	0.0	0.0	100.0	0.0
Dried open area with special vegetation	12,157.83	14.5	59.6	38.4	2.0
Open area with little or no vegetation	8,255.01	9.8	75.5	24.0	0.5
Water	578.56	0.7	5.4	67.0	27.5
Total	83,984.35	100.0			

3.2. Carbon sequestration in Triglav National Park

We obtained satisfactory results from the XGBoost-based downscaling from 500 to 10 m per pixel, with an average R^2 for all modelling rounds of 0.73, and a RMSE average value of 999.1 kgC/ha/year. Table 4 provides an overview of all validation metrics.

The negative bias value (–237.5) points at an overestimation of the NPP by the downscaled models. Regarding the spatial distribution of the NPP downscaled predictions, the map (Figure 3) follows the expected distribution of NPP values, with the lowest NPP values shown in the non-vegetated rocky mountain tops (mainly presented as Open area with little or no vegetation in Table 3) and gradual increase towards the forested slopes and valleys. The largest NPP values are located in the southern limit of the park following the same trend as the original 500 m MODIS NPP product.

NPP values were classified into four categories based on quantile distribution: low (<5,820 kgC/ha/year), moderate (5,820–7,410), high (7,410–8,250), and very high (>8,250), to allow comparison of productivity across sites, and can be seen in Table 5 and Figure 3.

Table 4: Prediction accuracies for the downscaled NPP using XGBoost models. Accuracies are reported using the coefficient of determination (R^2), root mean squared error (RMSE, expressed in the same units as the modeled maps), normalized root mean squared error (% RMSE over the range of original values within the training dataset), mean absolute error (MAE), and average bias (expressed in the same units as the modeled maps).

Metrics	R2	RMSE	nRMSE	MAE	Bias
	0.73	999.1	10%	727.5	–237.5

Figure 2: Distribution of land use types in the TNP. ➤ p. 83

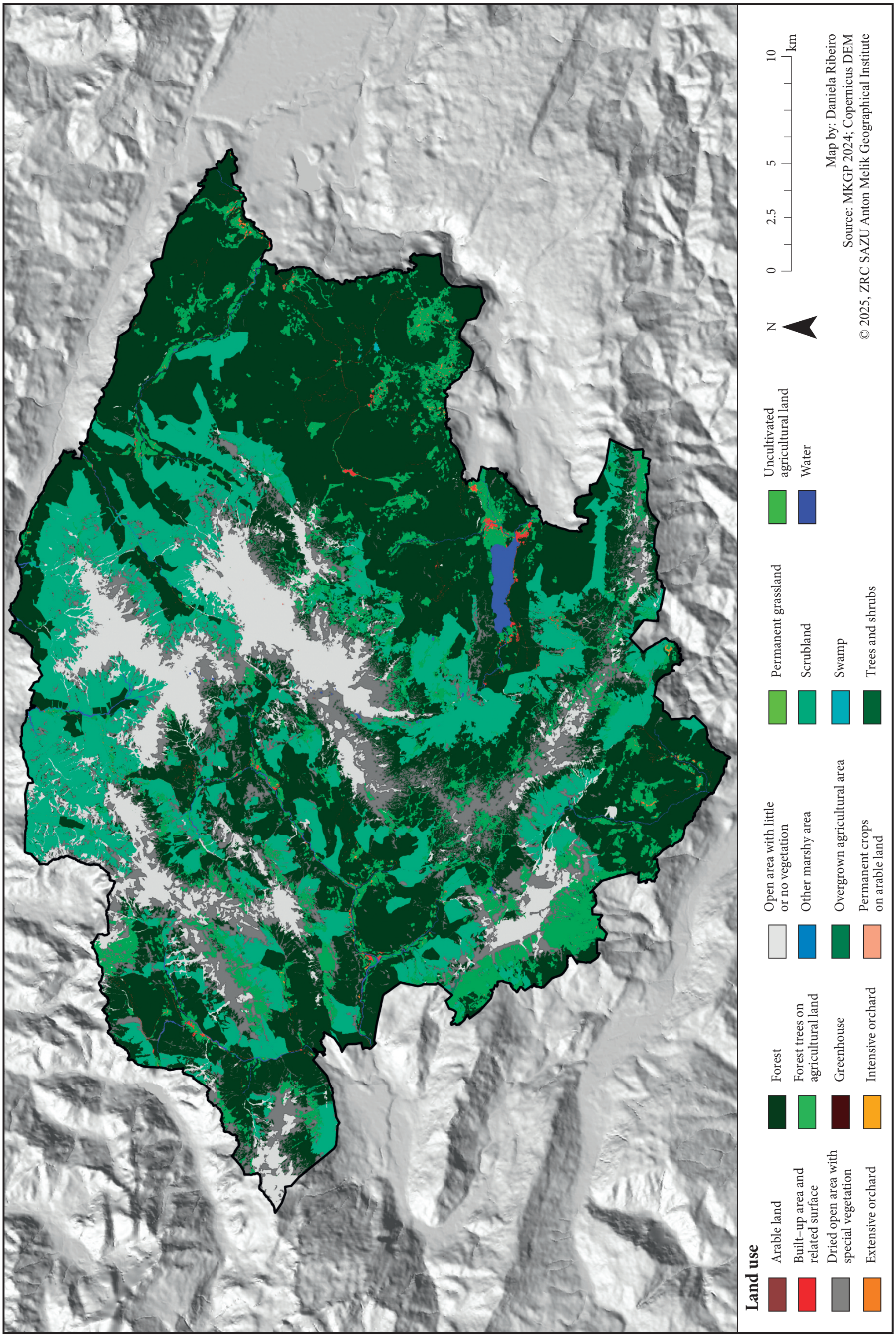

Land use
Arable land
Built-up area and related surface
Dried open area with special vegetation
Extensive orchard
Forest
Forest trees on agricultural land
Greenhouse
Intensive orchard
Open area with little or no vegetation
Other marshy area
Overgrown agricultural area
Permanent crops on arable land
Permanent grassland
Scrubland
Swamp
Trees and shrubs
Uncultivated agricultural land
Water
N
0 2.5 5 10 km
Map by: Daniela Ribeiro
Source: MKGP 2024; Copernicus DEM
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Table 5: Classification of mean NPP across land use types in the TNP.

Range mean NPP (kgC/ha/year)	Capacity for carbon sequestration
<5,820	Low productivity
5,820–7,410	Moderate productivity
7,410–8,250	High productivity
>8,250	Very high productivity

Table 6: Mean NPP by land use type in the TNP.

Land use type	Mean NPP (kgC/ha/year)	Capacity for carbon sequestration
Permanent crops on arable land	9,466	Very high productivity
Intensive orchard	8,193	High productivity
Extensive orchard	8,189	High productivity
Arable land	8,013	High productivity
Trees and shrubs	7,984	High productivity
Forest	7,841	High productivity
Overgrown agricultural area	7,652	High productivity
Scrubland	7,607	High productivity
Swamp	7,379	Moderate productivity
Permanent grassland	7,337	Moderate productivity
Uncultivated agricultural land	7,165	Moderate productivity
Forest trees on agricultural land	7,066	Moderate productivity
Built-up area and related surface	6,965	Moderate productivity
Other marshy area	6,673	Moderate productivity
Dried open area with special vegetation	5,398	Low productivity
Open area with little or no vegetation	3,669	Low productivity

The mean NPP – the average NPP (kgC/ha/year) for each land use type – can be seen in Table 6.

Additionally, we calculated the mean NPP for the TNP and each of its protection zones, as well as for the TNP's protective forests, to evaluate the influence of protective status on carbon sequestration capacity. In 2024, the mean NPP was 6,960 kgC/ha/year for the TNP as a whole, 6,022 kgC/ha/year for protection zone 1, 7,227 kgC/ha/year for protection zone 2, and 8,013 kgC/ha/year for protection zone 3 (Table 7). The mean NPP for protective forests was 7,571 kgC/ha/year, which is slightly lower than the mean NPP for all forested areas in the TNP (7,841 kgC/ha/year).

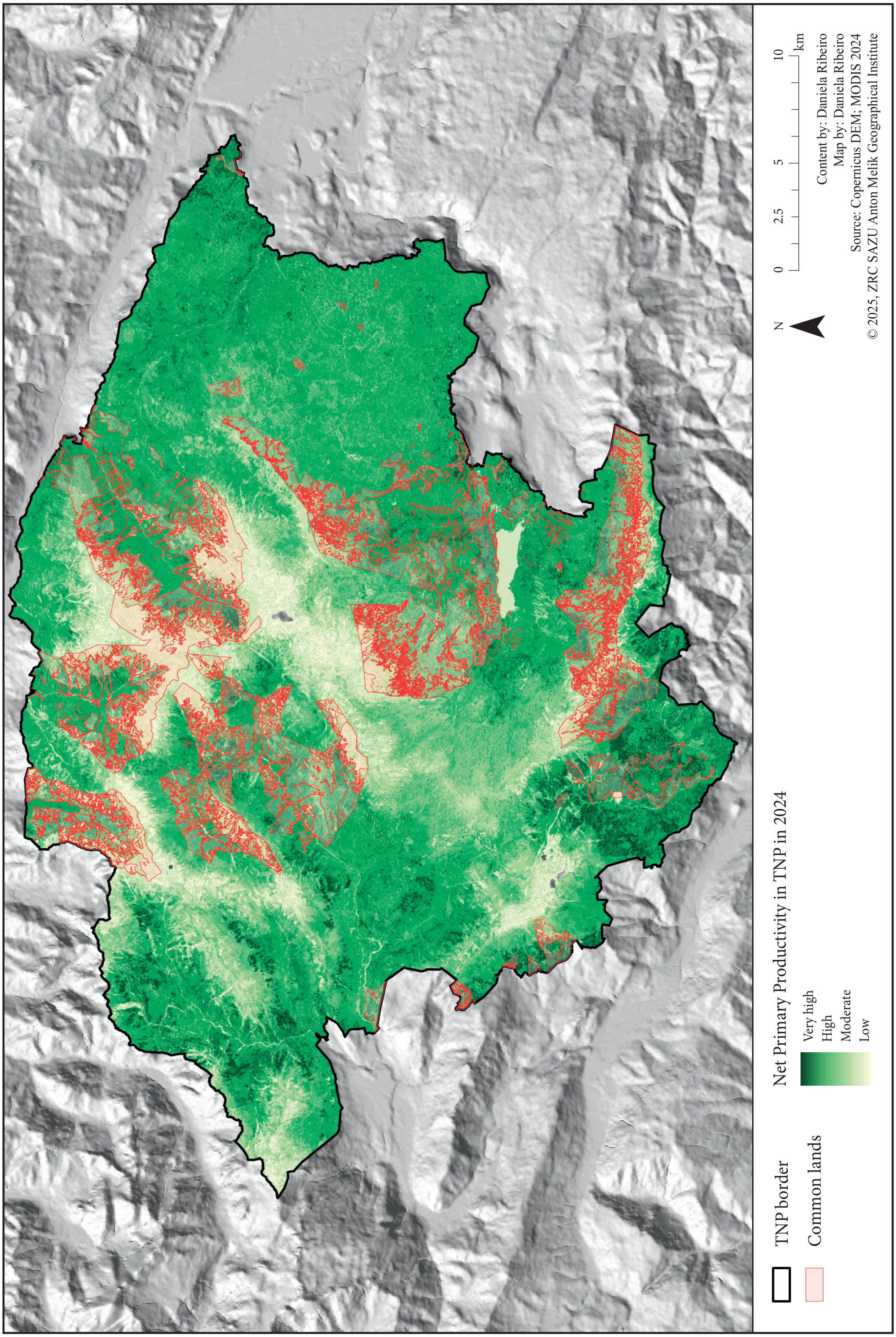
3.3 Carbon sequestration on common lands in Triglav National Park

Agrarian communities manage nearly one quarter of the TNP (19,400 ha). Forests dominate among the common land areas (31.9%), followed by high mountain areas, which include scrubland (28.7%), dried open areas with special vegetation (18.5%) and open areas with little or no vegetation (14.7%), which altogether account for 93.8% of all common land areas in the TNP. The mean NPP calculated in ArcGIS Pro for the combined area of all types of common lands in the TNP in 2024 was 6,510 kgC/ha/year, indicating a moderate capacity for carbon sequestration. However, the contribution of common lands to carbon sequestration is different in the different protection zones (Table 7).

Table 7: Contribution of common lands to carbon sequestration in the different protection zones of the TNP.

	Protection zone 1	Protection zone 2	Protection zone 3
Area of common lands (ha, %)	12,826 (66%)	5,026 (26%)	1,547 (8%)
Mean NPP in common lands (kgC/ha/year)	6,127	7,232	7,865
Mean NPP in the TNP (kgC/ha/year)	6,022	7,227	8,013

Figure 3: Distribution of NPP in the TNP. The map represents the downscaled (10 m per pixel) version of the original MODIS NPP. ➤ p. 85


TNP border
Common lands
Net Primary Productivity in TNP in 2024
Very high
High
Moderate
Low
N
0
2.5
5
10
km
Content by: Daniela Ribeiro
Map by: Daniela Ribeiro
Source: Copernicus DEM; MODIS 2024
© 2025, ZRC SAZU Anton Melik Geographical Institute

4 Discussion

The aim of this research was to improve understanding of the role of agrarian communities in the provision of ecosystem services through the application of quantitative and measurable methods. The study presents one of the first quantitative estimation assessments of its kind in Slovenia, and in comparable contexts elsewhere, thus contributing to the growing body of literature on common land management and the provision of ecosystem services (Pagot and Gatto 2024; Gomes et al. 2025).

4.1 Interpretation of carbon sequestration in Triglav National Park

The analysis of mean NPP across land use types and protective zones reveals differences that reflect both land management and ecological characteristics of this alpine park. Permanent crops on arable land exhibit the highest mean NPP values (9,466 kgC/ha/year), likely due to practices that enhance biomass productivity. Orchards (extensive and intensive) and arable land follow closely behind, showing that farmland contributes significantly to carbon fixation.

The observed NPP values for forested areas, including forests, and trees and shrubs in the TNP (app. 7,841–7,984 kgC/ha/year) are within the ranges reported for temperate and montane forest ecosystems in the literature. These values can vary substantially depending on species composition, elevation, stand age, and site productivity (e.g., Clark et al. 2001; Tang et al. 2010). However, this estimate represents an upper bound on potential carbon uptake in the study area. Actual net carbon sequestration in temperate forests is generally lower, according to Tölgyesi et al. (2025) between 1,240 and 2,800 kgC/ha/year. Despite covering large parts of the TNP and being inherently productive ecosystems, forests are underrepresented in MODIS-derived NPP estimates. This is likely due to a combination of fragmented polygon sizes, causing mixed-pixel effects, and terrain-related limitations (e.g., slope, shadows, and seasonal snow cover), which reduce the reliability of satellite-based productivity detection. These results highlight the importance of resolution-aware analysis and suggest that forest carbon dynamics in alpine landscapes may require higher-resolution or field-calibrated data for accurate quantification.

In particular rocky surfaces and scrublands (*Pinus mugo*) contribute the least to carbon sequestration, reflecting limited photosynthetic activity in these land cover types, which aligns with expectations. Overall, these results highlight the heterogeneity of carbon uptake across land use types in the TNP. They also underscore the role of agricultural land and forests in maintaining primary productivity, even in a mountainous protected area context. This suggests that land use mosaics, including traditionally managed agricultural systems, can complement forest ecosystems in supporting carbon sequestration goals.

Built-up areas show surprisingly high NPP, likely due to mixed-classification pixels. Although certain land use types (e.g., Permanent crops on arable land) exhibit a relatively high carbon sequestration potential per unit area, their limited spatial extent within the study area constrains their overall contribution to total carbon uptake. Conversely, more widespread land use categories (e.g., Permanent grassland), despite having lower mean NPP values, may play a more significant role in total carbon sequestration due to their broader coverage. This highlights the importance of considering both sequestration efficiency and spatial distribution when evaluating the carbon dynamics at landscape level.

In addition, the protection status impacts carbon sequestration capacity. Protection zone 1, where grazing is allowed but forest management is excluded, shows the lowest mean NPP, while protection zone 3 has the highest capacity for carbon sequestration. This difference is partly related to land use composition: as shown in Table 3, protection zone 1 is largely dominated by rocky surfaces and scrublands, whereas forest, which is the predominant land use in the TNP, is much more prevalent in protection zones 2 and 3.

Similarly, the mean NPP for protective forests (7,571 kgC/ha/year), which are predominant in Protective zones 1 and 2, was lower than the mean NPP for all forested areas within the TNP (7,841 kgC/ha/year). This result may reflect ecological and structural characteristics of protective forests in the TNP that play a key role in preventing natural disasters (such as erosion, landslides, etc.) as presented by Rozman and Arih (2015). These forests are often located on steep slopes, on marginal soils or at high elevations, where environmental conditions are less favourable for biomass production (Klopčič et al. 2015) but are crucial for their protective role (Rozman and Arih 2015). In addition, these forests in the TNP, especially if they are located in the first protection zone, are not managed (e.g., for timber production) and interventions may be limited to maintain stability and protective functions (Poljanec et al. 2015).

In any case, it is important to mention that sequestration is just one way in which forests contribute to mitigate climate change. Carbon sinks are even more important, so it is crucial to preserve existing forests that store carbon, even if they are older and have a lower capacity for carbon sequestration (Kilpeläinen and Peltola 2022).

4.2 The role of common lands

In addition to their significant contribution to biodiversity and nature protection presented by Šmid Hribar (2025), we anticipated that common lands in the TNP would also play a substantial role in carbon sequestration, especially considering that nearly a quarter (24.0%) of the TNP is managed by agrarian communities, and that forests and scrubland cover more than half (60.6%) of their common lands. However, this expectation was tempered by the fact that 33.2% of these common lands consist of rocky surfaces and scrublands all of which have significantly lower carbon sequestration capacity (see Table 6). In addition, two-thirds of their common lands (Table 7), are in protection zone 1, where forest management is not allowed. As a result the mean NPP of all common lands and their capacity to carbon sequestration was considerably reduced. Thus, based on our assessment, common lands in the TNP exhibit a moderate overall capacity for carbon sequestration. While this contribution is lower than initially expected, it is important to highlight that the extent of spatial distribution of communally owned forests and scrublands accounts for just over a fifth (21.5%) of all forested and scrubland areas in the park and 14.0% of the total area of the TNP, demonstrate a higher carbon sequestration capacity, despite the mean NPP across all common lands remains moderate. Taking this into account, we conclude that forest commons in the TNP still make a meaningful contribution to carbon sequestration.

On the other hand this analysis might also suggest that protective forests within common lands in Protective zone 1 in the TNP more significantly support other ecosystem services, such as erosion prevention, wind protection, nature-based recreation, etc. Therefore, further empirical research is needed to better assess the common lands contribution for broader society.

Furthermore, although our results indicate a lower mean NPP in common lands within the TNP compared to those reported for common lands in Northern Portugal (Gomes et al. 2025), this difference likely reflects contrasting ecological conditions, forest types, and climatic influences between the Alpine and Sub-Mediterranean regions as well as differences in forest management practices (as mentioned in Table 1, in the TNP protection zone 1 forest management is not allowed, while protection zones 2 and 3 allow certain practices). The Alpine landscape of the TNP is characterized by cooler temperatures, shorter growing seasons, and higher elevations, which can constrain productivity. In contrast, the sub-Mediterranean conditions in Northern Portugal, particularly in managed *Pinus pinaster* forests, may promote higher biomass production and accumulation under favorable site conditions.

4.3 Limitations

While the MODIS-derived NPP data provide valuable insights into spatial patterns of vegetation productivity, there are several limitations to using this product as a proxy for carbon sequestration. First, MODIS NPP estimates are based on light use efficiency models and a coarse spatial resolution (500 m), which means that each pixel represents the average productivity of a large area that may contain multiple land use types or vegetation structures. This coarse resolution cannot accurately capture fine-scale heterogeneity. Thus, small features such as small agricultural plots or urban structures may be underrepresented within NPP pixels, leading to generalisations that reduce spatial accuracy. Second, the MODIS NPP does not account for carbon loss due to disturbance (e.g., forest fires, erosion, etc.) or carbon stored in long-lived biomass pools such as deadwood or soil organic matter. It therefore represents short-term carbon uptake rather than long-term sequestration potential. Furthermore, the algorithm relies on vegetation indices, which can be saturated in dense tree canopies and influenced by atmospheric or topographic effects, leading to uncertainties. Therefore, while the MODIS NPP is a useful comparative tool, it should be interpreted with caution and ideally supplemented with field measurements or higher resolution data to enable robust carbon accounting.

While downscaling MODIS NPP data with Sentinel-2 vegetation indices and HR-VPP layers allows for finer spatial resolution (10 m) and a better representation of land use heterogeneity, this method also comes with limitations. First, the downscaled product is still subject to the temporal and biophysical assumptions of the original MODIS NPP data. The improved spatial detail does not reflect direct measurements of NPP at 10 m, but derived patterns based on vegetation indices and land cover features from Sentinel 2. Downscaling can also introduce spatial leakage, whereby signals from adjacent land-cover types affect the downscaled estimates, so NPP from nearby features influences a pixel's predicted value. Additionally, although XGBoost can predict beyond the range observed in training, predictive performance typically degrades when extrapolating outside the MODIS-supported NPP range. As a result, estimates are effectively constrained by the training distribution, with higher uncertainty near or beyond its bounds. Due to the aforementioned uncertainties, the downscaling process can potentially lead to an overestimation of NPP values at pixel level. Some of these limitations could be addressed using LiDAR-derived vegetation height. While this approach may improve the overall precision of estimates, it could disproportionately weight predictions towards tree-dominated areas. Moreover, the typically low temporal resolution of LiDAR products fails to capture management-driven dynamics. In summary, although downscaling improves spatial resolution and visual coherence with land use maps, it should be interpreted as a model-derived approximation of carbon sequestration.

5 Conclusions

We hypothesised that agrarian communities greatly contribute to the sustainable management of their common lands. However, the available literature lacks information on their management, which is an area for future qualitative studies (e.g., semi-structured interviews with agrarian community representatives). This study offers one of the first estimation insights into the role of agrarian communities in ecosystem service provision focusing specifically on carbon sequestration in the TNP. Our findings underscore the need to assess both, carbon sequestration potential and spatial extent when evaluating land use contributions to carbon dynamics, as high productivity alone does not necessarily translate into greater overall impact at the landscape scale.

The analysis of common lands managed by agrarian communities showed that, although their overall carbon sequestration capacity is moderate, particularly their forests and scrublands, i.e. forest commons, covering 14.0% of the TNP and demonstrating high sequestration capacity, still play a key role in supporting this essential regulating ecosystem service. However, when it comes to forests, it is important to refer back to one of the key findings from Slovenia's National Inventory Document 2024 that Slovenian forests are gradually losing their carbon sequestration capacity. Based on our analysis, this trend suggests that private forest owners in Slovenia, including agrarian communities (not only those in the TNP, where management is constrained by the protection regime), have an opportunity to adopt improved management practices that would enhance their forests' carbon sequestration. These practices include: moderate growth accumulation, reduced harvesting in protective forests, expanding managed forests without intensive interventions, preserving or increasing unmanaged forests (e.g., forest reserves, forests in the TNP), maintaining long rotation periods (especially in preserved forests), conserving forest areas in agricultural and urban landscapes, and strengthening forest resilience to climate change and its impacts (Poljanec et al. 2023). Through various national and European financial mechanisms (e.g., the Forest Fund, the Climate Change Fund, the Rural Development Programme, etc.), Slovenia already finances measures that contribute to improving the condition of forest stands, making them more resilient in the long term to climate change impacts (such as storms and droughts), and capable of ensuring effective carbon sequestration (Konjar et al. 2023). In addition, as previously mentioned, carbon storage of existing forests with their enourmous capacities to retain carbon is arguably even more important than sequestration for mitigating climate change, which makes the preservation of existing forests (and other intact ecosystems) essential (Cook-Patton et al. 2020). From this perspective, communaly managed forests play a notable role. Still, as strongly highlighted by Cook-Patton et al. (2020) and Tölgyesi et al. (2025) carbon sequestration and storage should not be seen as substitutes for reducing greenhouse gas emissions. Reducing these anthropogenic emissions remains essential.

Last but not least, future studies could benefit from incorporating data from the European Space Agency's Biomass satellite. This mission is designed to provide unprecedented insights into how much carbon is stored in the world's forests. As it is the first satellite with signal capable of penetrating forest canopies to measure woody biomass – trunks, branches and stems. Integrating such data would enhance the precision of carbon sequestration estimates, particularly in complex landscapes like alpine environments and the long-term role of communal lands in climate regulation.

ACKNOWLEDGEMENT: We greatly appreciate the valuable suggestions for improvement made by all reviewers. The research was financially supported by the Slovenian Research and Innovation Agency research core funding program »Geography of Slovenia« (P6-0101). This article was also supported by the SELINA project funded by the European Union's Horizon Europe Research and Innovation Programme under grant agreement No 101060415. Additional support was provided by the project CREATE (Cross-REalm modelling and assessment of Aquatic ecosystem services: Towards a science-based design of Nature-based solutions to tackle Eutrophication), funded under the Water4All 2023 Joint Transnational Call, and supported by the European Union's Horizon Europe research and innovation programme (Grant No 367850).

RESEARCH DATA: For information on the availability of research data related to the study, please visitthe article webpage: https://doi.org/10.3986/AGS.14491.

6 References

Bischl, B., Lang, M., Kotthoff, L., Schiffner, J., Richter, J., Studerus, E., Casalicchio, G., Jones, Z. M. 2016: mlr: Machine learning in R. *Journal of Machine Learning Research* 17-170.

Bogataj, N., Krč, J. 2014: A forest commons revival in Slovenia. *Society and Natural Resources* 27-8. https://doi.org/10.1080/08941920.2014.918225

Bogataj, N., Krč., J. 2023: Towards the efficient response of forest owners to large-scale forest damage: An example of forest commons. *Acta geographica Slovenica* 63-3. https://doi.org/10.3986/AGS.11084

Brockerhoff, E. G., Barbaro, L., Castagneyrol, B., Forrester, D. I., Gardiner, B., González-Olabarria, J. R., Lyver, P. O'B. et al. 2017: Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodiversity and Conservation* 26. https://doi.org/10.1007/s10531-017-1453-2

Cao, M., Woodward, F. I. 1998: Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology* 4-2. https://doi.org/10.1046/j.1365-2486.1998.00125.x

Chen, T., He, T., Benesty, M., Khotilovich, V. 2019: Package 'xgboost' (Version 0.90). *Program.* R package.

Clark, D. A., Brown, S., Kicklighter, D. W., Chambers, J. Q., Thomlinson, J. R., Ni, J. 2001: Measuring net primary production in forests: Concepts and field methods. *Ecological Applications* 11-2. https://doi.org/10.2307/3060894

Cook-Patton, S. C., Leavitt, S. M., Gibbs, D., Harris, N. L., Lister, K., Anderson-Teixeira, K. J., Briggs, R. D. et al. 2020: Mapping carbon accumulation potential from global natural forest regrowth. *Nature* 585. https://doi.org/10.1038/s41586-020-2686-x

De Leeuw, J., Rizayeva, A., Namazov, E., Bayramov, E., Marshall, M. T., Etzold, J., Neudert, R. 2019: Application of the MODIS MOD 17 Net Primary Production product in grassland carrying capacity assessment. *International Journal of Applied Earth Observation and Geoinformation* 78. https://doi.org/10.1016/j.jag.2018.09.014

European Commission 2025: Commission assessment of the final updated National Energy and Climate Plan of Slovenia. *Report*. Directorate-General for Communication.

Gatto, P., Bogataj, N. 2015: Disturbances, robustness and adaptation in forest commons: Comparative insights from two cases in the South-eastern Alps. *Forest Policy and Economics* 58. https://doi.org/10.1016/j.forpol.2015.03.011

Gitelson, A. A., Kaufman, Y. J., Merzlyak, M. N. 1996: Use of a green channel in remote sensing of global vegetation from EOS-MODIS. *Remote Sensing of Environment* 58-3. https://doi.org/10.1016/S0034-4257(96)00072-7

Goetz, S. J., Prince, S. D. 1996: Remote sensing of net primary production in boreal forest stands. *Agricultural and Forest Meteorology* 78-3,4. https://doi.org/10.1016/0168-1923(95)02268-6

Gomes, P., Ribeiro, D., Lopes, D. 2025: Assessing the contribution of communal lands to ecosystem services: A case study from Portugal. *Acta geographica Slovenica* 65-3. https://doi.org/10.3986/AGS.14339

Haines-Young, R. 2023: Common International Classification of Ecosystem Services (CICES) V5.2 and guidance on the application of the revised structure. *Guidance*. Fabis Consulting.

Haller, T., Bertogliati, M., Liechti, K., Stuber, M., Viallon F.-X., Wunderli, R. 2021: Transformation and diversity: Synthesis of the case studies. In: Balancing the Commons in Switzerland: Institutional Transformations and Sustainable Innovations. London. https://doi.org/10.4324/9781003043263-13

Heinsch, F. A., Reeves, M., Votava, P., Kang, S., Milesi, C., Zhao, M., Glassy, J. et al. 2003: User's guide GPP and NPP (MOD17A2/A3) products NASA MODIS land algorithm. Version 2.0. *User's manual*. NASA MODIS Land Team.

Hijmans, R. J., Van Etten, J., Cheng, J., Mattiuzzi, M., Sumner, M., Greenberg, J. A., Hijmans, M. R. J. 2015: Package 'raster'. *Program.* R package.

Hu, Y., Zhang, Q., Hu, S., Xiao, G., Chen, X., Wang, J., Qi, Y. et al. 2022: Research progress and prospects of ecosystem carbon sequestration under climate change (1992–2022). *Ecological Indicators* 145. https://doi.org/10.1016/j.ecolind.2022.109656

Jiang, Z., Huete, A. R., Didan, K., Miura, T. 2008: Development of a two-band enhanced vegetation index without a blue band. *Remote Sensing of Environment* 112-10. https://doi.org/10.1016/j.rse.2008.06.006

Jönsson, P., Cai, Z., Melaas, E., Friedl, M. A., Eklundh, L. 2018: A method for robust estimation of vegetation seasonality from Landsat and Sentinel-2 time series data. *Remote Sensing* 10-4. https://doi.org/10.3390/rs10040635

Jönsson, P., Eklundh, L. 2004: TIMESAT – a program for analyzing time-series of satellite sensor data. *Computers & Geosciences* 30-8. https://doi.org/10.1016/j.cageo.2004.05.006

Kilpeläinen, A., Peltola, H. 2022: Carbon sequestration and storage in European forests. In: Forest Bioeconomy and Climate Change. *Managing Forest Ecosystems* 42. Springer. https://doi.org/10.1007/978-3-030-99206-4_6

Klopčič, M., Pisek, R., Poljanec, A. 2015: Razširjenost, zgradba in razvojne spremembe gozdov. In: Gozdovi v Triglavskem narodnem parku: ekologija in upravljanje. Ljubljana.

Konjar, M., Beguš, J., Vertelj, A., Bončina, Ž. 2022: Ukrepi za optimizacijo ponorov ogljika v gozdovih in njihovo financiranje. *Technical guidance*. Zavod za gozdove Slovenije.

Main-Knorn, M., Pflug, B., Louis, J., Debaecker, V., Müller-Wilm, U., Gascon, F. 2017: Sen2Cor for sentinel-2. In: Image and Signal Processing for Remote Sensing XXIII. *Proceedings* Volume 10427. https://doi.org/10.1117/12.2278218

Melillo, J. M, McGuire, A. D., Kicklighter, D. W., Moore, B., Vorosmarty, C. J., Schloss, A. L. 1993: Global climate change and terrestrial net primary production. Nature 363. https://doi.org/10.1038/363234a0

Nogueira, J., Araújo, J. P., Alonso, J. M., Simões, S. 2023: Common lands, landscape management and rural development: A case study in a mountain village in northwest Portugal. *Acta geographica Slovenica* 63-3. https://doi.org/10.3986/AGS.11081

Pagot, G., Gatto, P. 2024: Challenges for community-owned forests between traditional and new uses of forests: A Q-methodology study applied to an alpine case. *Trees, Forests and People* 18. https://doi.org/10.1016/j.tfp.2024.100688

Pagot, G., Šmid Hribar, M., Rail, L. F., Walters, G., Hymas, O., Liechti, K., Haller, T. et al. 2025: Territories of commons: A review of common land organizations and institutions in the European Alps. *Environmental Research Letters* 20-6. https://doi.org/10.1088/1748-9326/add1f4

Pintar, A. M., Ferreira, A., Höfferle, P., Japelj, A. 2025: The impact of sanitary felling during large-scale disturbances on regulating ecosystem services in Norway spruce-dominated Pre-Alpine beech forests of Slovenia. *Forests* 16-11. https://doi.org/10.3390/f16111631

Poljanec, A., Gartner, A., Mlekuž, I., Jerala, B., Klopčič, M. 2015: Značilnosti gospodarjenja z gozdovi. In: Gozdovi v Triglavskem narodnem parku: ekologija in upravljanje. Ljubljana.

Poljanec, A., Guček, M., Simončič, T., Stergar, M., Marenče, M., Pisek, R. 2023: Območni gozdnogospodarski in lovsko upravljavski načrti za obdobje 2021–2030 – kompendij. Ljubljana.

Rouse, J. W., Haas, R. H., Schell, J. A., Deering, D. W. 1974: Monitoring vegetation systems in the great plains with ERTS. In: Third Earth Reserves Technology Satellite Symposium. NASA.

Rozman, R., Arih, A. 2015: Naravovarstveni pomen gozdov. In: Gozdovi v Triglavskem narodnem parku: ekologija in upravljanje. Ljubljana.

Slovenia's National Inventory Document 2024 2024: GHG emissions inventories 1986–2022. *Report*. Slovenian Environment Agency, Ministry of the Environment, Climate, and Energy.

Smets, B., Cai, Z., Eklundh, L., Tian, F., Bonte, K., Van Hoost, R., De Roo, B. et al. 2023: HR-VPP product user manual: Seasonal trajectories and VPP parameters (Issue 2.3). European Environment Agency.

Šmid Hribar, M. 2025: Ten years after the new Agrarian Communities Act: The state of agrarian communities in the Gorenjska region. *Geografski vestnik* 97 (in press).
Šmid Hribar, M., Hori, K., Urbanc, M., Saito, O., Zorn, M. 2023: Evolution and new potentials of landscape commons: Insights from Japan and Slovenia. *Ecosystem Services* 59. https://doi.org/10.1016/j.ecoser.2022.101499
Šmid Hribar, M., Japelj, A., Rac, I., Vurunić, S., Ribeiro, D. 2025: Challenges related to participatory assessment of ecosystem services in protected areas in Slovenia. *One Ecosystem* 10. https://doi.org/10.3897/oneeco.10.e163691
Tang, G., Beckage, B., Smith, B., Miller, P. A. 2010: Estimating potential forest NPP, biomass and their climatic sensitivity in New England using a dynamic ecosystem model. *Ecosphere* 1-6. https://doi.org/10.1890/ES10-00087.1
Tölgyesi, C., Csikós, N., Temperton, V. M., Buisson, E., Silveira, F. A. O., Lehmann, C. E. R., Török, P. et al. 2025: Limited carbon sequestration potential from global ecosystem restoration. *Nature Geoscience* 18. https://doi.org/10.1038/s41561-025-01742-z
Villoslada, M., Berner, L. T., Juutinen, S., Ylänne, H., Kumpula, T. 2024: Upscaling vascular aboveground biomass and topsoil moisture of subarctic fens from Unoccupied Aerial Vehicles (UAVs) to satellite level. *Science of the Total Environment* 933. https://doi.org/10.1016/j.scitotenv.2024.173049
Zavod za gozdove Slovenije 2024: Pregledovalnik podatkov o gozdovih, Varovalni gozdovi. *Data viewer*.
Zhang, H., Eziz, A., Xiao, J., Tao, S., Wang, S., Tang, Z., Zhu., J. et al. 2019: High-resolution vegetation mapping using eXtreme gradient boosting based on extensive features. *Remote Sensing* 11-12. https://doi.org/10.3390/rs11121505